

A DIRECT CURRENT RECTIFICATION SCHEME FOR MICROWAVE SPACE POWER
CONVERSION USING TRAVELING WAVE ELECTRON ACCELERATION

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The formation of the Vision-21 conference held three years ago allowed the present author to reflect and speculate on the problem of converting electromagnetic energy to a direct current by essentially reversing the process used in traveling wave tubes that converts energy in the form of a direct current to electromagnetic energy. The idea was to use the electric field of the electromagnetic wave to produce electrons through the field emission process and accelerate these electrons by the same field to produce an electric current across a large potential difference. The acceleration process was that of cyclotron auto-resonance. Since that time, this rather speculative idea has been developed into a method that shows great promise and for which a patent is pending and a prototype design will be demonstrated in a potential laser power beaming application. From the point of view of the author, a forum such as Vision-21 is becoming an essential component in the rather conservative climate in which our initiatives for space exploration are presently formed. Exchanges such as Vision-21 not only allow us to deviate from the "by-the-book" approach and rediscover the ability and power of imagination, but provides for the discussion of ideas hitherto considered "crazy" so that they may be given the chance to transcend from the level of eccentricity to applicability.

The advent of future space and planetary exploration for the 21st century has precipitated the usual considerations of energy transfer, particularly in the form of electrical power, to support various exploration activities. Even point-to-point power transmission to earth from space or between two points on earth is being reconsidered.¹ The need to distribute energy from a minimal number of centralized sources in an efficient manner has given rise to the reconsideration of microwave power transmission and its related conversion to useful electrical power. However, such considerations, especially those of the well known Microwave Power Transmission System Study procured by NASA in 1975, have been traditionally impeded by the constraints induced by the use of relatively long wavelengths (i.e. centimeter wavelengths at the proposed operating frequency of 2.45 GHz) and the attendant large transmitting and receiving structures with the prevailing small coupling efficiencies. These drawbacks have stimulated interest in the use of smaller wavelengths, e.g., those peculiar to high energy carbon dioxide or free electron lasers the

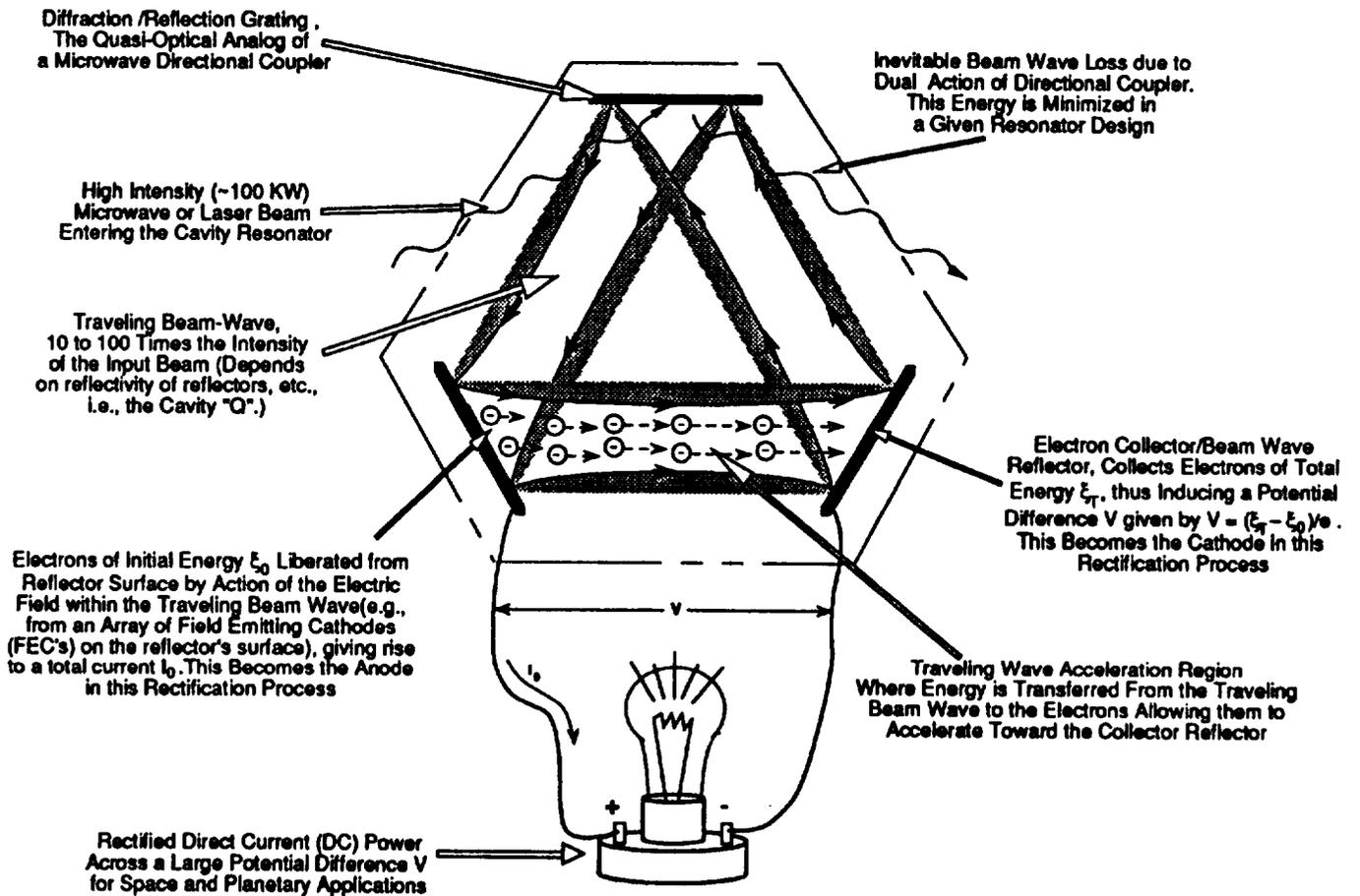
wavelengths of which are 10,000 times smaller than microwave wavelengths, thus allowing the use of electrodynamic structures 10,000 smaller than those at the microwave wavelengths. In particular, this "laser power beaming" has been recently proposed² for ground-to-space energy transmission as well as for low earth orbit (LEO) to geosynchronous orbit (GEO) payload delivery via plasma engine propulsion.

This paper will address one area of this multifaceted problem, viz, the conversion of energy which resides in a received electromagnetic field to that which is in the form of a direct current across a potential difference which can be used to provide electric power for a number of space and planetary applications. The novel method for electromagnetic wave power rectification to be described here is applicable over a wide range of wavelengths within the electromagnetic spectrum. More importantly, however, it can be made to have the capability to be entirely "passive", i.e., not having to rely on additional energy sources, other than the received electromagnetic field, to induce the creation of electrons which constitutes the resulting direct current.

In particular, a conversion process will briefly be presented that demonstrates how, by establishing a traveling electromagnetic wave field within a three mirror traveling-wave open resonator, electrons are accelerated by the wave, via the action of one of two possible traveling-wave acceleration mechanisms, to several times their rest energy, thus establishing an electric current over a large potential difference. The electrons needed in this process can also issue from one of several possible mechanisms; they can be "actively" created by thermionic emission which, of course, would require the need for an auxiliary power source, or they can be "passively" created by field emission (i.e., cold emission) processes through the action of the resonator field on an array of field emission cathodes or surfaces appropriately placed on one of the three resonator mirrors. The open resonator design of this rectification process allows for its use in the frequency spectrum from the quasi-optical frequencies of about 90 GHz to the infrared frequencies in the Terahertz range. The method is depicted in Figure 1 and its three novel features, i.e., the use of a quasi-optical diffraction grating to act analogously as a microwave directional coupler, the use of a passive electron emission process, and the subsequent

Figure 1

A DC RECTIFIER FOR MICROWAVE SPACE POWER CONVERSION USING TRAVELING -WAVE ELECTRON ACCELERATION *



acceleration of these electrons by the traveling-wave field established within the resonator, will now be discussed in what is to follow. Only the most important highlights that have issued from a detailed theoretical analysis will be presented.

Quasi-Optical Directional Coupler - A Diffraction/Reflection Grating

The introduction into the three mirror resonator of the electromagnetic field, the energy of which is to be converted to direct current, occurs by the use of a diffraction/reflection grating which is not only operated in the usual reflection mode, but also in a diffraction mode. As is well known, the grating action scatters the incident beam of wavelength λ , occurring at an angle of incidence θ_i , into diffracted beams oriented along angles θ_n that are given by

$$\sin\theta_n = \sin\theta_i + \frac{n\lambda}{d}; \quad \frac{\lambda}{d} \geq \frac{2}{3}, \quad n = 0, \pm 1, \pm 2, \dots$$

where d is the grating spacing. Each of the diffracted beams has associated with it a corresponding reflection coefficient r_n . As these

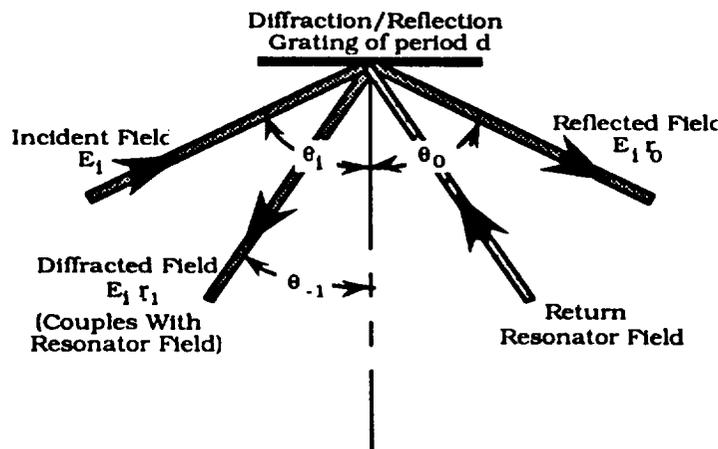


Figure 2
Detail of incident and diffraction angles at the Diffraction/Reflection Grating

coefficients are a function of the grating material as well as the groove depth, the grating structure can be selected so as to support only two diffracted beams³, viz, the $n=0$ beam, which is the classical reflected beam at the angle $\theta_1=\theta_0$, and the $n=-1$ beam which is a retro-reflected beam at the angle θ_{-1} given by

$$\sin\theta_{-1} = \sin\theta_1 - \frac{\lambda}{d}$$

The associated reflection coefficients are related, through conservation of energy (assuming the grating material has negligible absorption), by the relationship

$$r_0^2 + r_{-1}^2 = 1$$

As shown in Figure 2, it is the $n=-1$ beam that couples the incident energy into the cavity, and thus suggests that the coefficient r_{-1} should be maximized. However, the same diffractive process occurs on the other side of the grating and tends to couple energy back out of the cavity. Thus, r_{-1} cannot be arbitrarily maximized without constraints. A complete analysis incorporating the power incident into the cavity, the energy which resides in the traveling wave field, as well as that which is coupled out of the cavity, and the normalized beam current I_n due to the subsequent electron acceleration which occurs between two of the three cavity mirrors, yields the optimal values for r_{-1} given by

$$r_{-1_{opt}} = \left(\frac{\gamma_{acc} L}{3} \right)^{1/2} \left[\frac{I_n}{2} + \left(\frac{I_n^2}{4} + \frac{3\gamma_{tot}}{\gamma_{acc}} \right)^{1/2} \right]$$

where γ_{acc} is the attenuation incurred by the traveling wave in the accelerator portion of the cavity and γ_{tot} is the total attenuation of the wave

field around the entire length L of the cavity. Of course, the beam current I_n will be a function of the particular acceleration mechanism chosen as well as a function of the cavity field strength. Hence, even though one can visualize a non-linear problem forming, it is obvious how one can proceed in designing and implementing a diffraction/reflection grating to couple power into the cavity as well as sustaining the traveling wave process within the cavity in the presence of electron acceleration by the wave field.

Electrons for the Acceleration Process

Electrons with which the direct current is created, as well as the large potential difference by their subsequent acceleration, can most easily be introduced into the traveling wave field of the cavity by the suitable placement of an electron gun behind the mirror which follows the diffraction/reflection grating. This "active" electron production technique would require the use of a small auxiliary power source to provide for the thermionic emission. Although such a scenario would provide for a respectable power conversion method, it will inherently have a smaller conversion efficiency since one must count the auxiliary power source as a loss. Furthermore, the need to carry such an auxiliary source with the power converter can add weight to a mission as well as decrease the reliability of the operation of the power converter. Thus, maintaining this active method of electron production as a last alternative, one is motivated to consider "passive" methods of electron production such as is realized in cold field emission.

Recent advances in the materials and production of arrays of field emission cathodes (FEC) make considerations of such passive electron production possible⁴. What is envisioned is an array of FEC's placed in the center of the mirror where the electric field of the traveling wave will have its largest value. With a nominal value of the work function of about 2 eV for typical FEC materials and a tip magnification factor of $\beta=1000$, calculations via Fowler-Nordheim theory show that an electric field strength within the resonator of 1×10^6 V/m is required at the tip of these cathodes to elicit a

current density of about 50 A/cm² from them. Such field strengths place a lower limit on the operation of this passive generation scheme.

One can also consider other electron emission schemes such as liquid metal field emission⁵, etc. Further considerations of field strength versus breakdown voltages, ohmic heating, etc., will help define the particular field emission method to be employed.

Finally, although the energy at which the electrons are emitted will be described by an distribution over a range of values, it is sufficient to assume that they are certainly non-relativistic at this point and they therefore are approximately represented by their rest energy ξ_0 .

Traveling- Wave Electron Acceleration

Once the electrons have been generated by one of the mechanisms discussed above, it remains to provide a mechanism through which energy can be transferred from the electromagnetic traveling wave field to the electrons. The first obvious choice is to employ cyclotron auto-resonance acceleration⁶ by establishing a constant magnetic field directed longitudinally along the acceleration axis. Here, the condition

$$\gamma(z) \left(1 - \frac{v_z(z)}{v_\phi(z)} \right) = \frac{\omega_B(z)}{\omega}$$

must always be maintained between the electron velocity $v_z(z)$ along the acceleration axis (taken here to be the z-axis), the associated relativistic factor $\gamma(z)$, the Larmor or cyclotron frequency $\omega_B(z)$, the phase velocity $v_\phi(z)$ of the traveling wave field (all of which are, in general, functions of the position z along the acceleration axis), and the angular frequency of the traveling wave field ω . In the case of the open resonator structure considered here, its mode of operation will be such that $v_\phi(z) \approx c$. Furthermore, since the initial velocity of the emitted electrons (at the point $z=0$) is such that $\gamma(0) = 1$, one sees from the above relation that

$$\omega_B(0) \equiv \frac{eB(0)}{mc} = \omega$$

where $B(0)$ is the intensity of the magnetic field needed at the beginning of acceleration, e is the electron charge, and m is its mass.

Hence, one sees that for a wave frequency of 10 GHz, i.e., $\omega = 6.28 \times 10^{10} \text{ s}^{-1}$, $B(0) = 3.5 \text{ kG}$, an easily realizable magnetic field using light weight magnetic materials. However, at 100 GHz, one has $B(0) = 35 \text{ kG}$ which starts to require the use of much larger and heavier magnetic materials. As frequencies higher than 100 GHz are approached, physically unachievable magnetic fields are required. Thus, the use of cyclotron auto-resonance is not a viable acceleration scheme for this power conversion process if it is to be considered at the infrared or optical frequencies proposed for laser power beaming.

One can exploit the spatial and temporal structure of a pulsed gaussian beam that would appear in the resonator in the case of pulsed laser beaming, and discover another possible electron acceleration mechanism. This mechanism, especially its use in this particular application, must remain proprietary due to the pending patent disclosure of this rectification process, and cannot be disclosed in its entirety at this time. However, it is possible to state that the region of applicability of this second traveling wave acceleration process is defined by the constraint

$$\frac{v_z(0)}{c} \gg 2\pi\gamma(0) \frac{\omega_B(0)}{\omega}$$

which significantly eases the requirements for a magnetic field. In the case of a wave field of a wavelength of $10.6 \mu\text{m}$ (a typical CO_2 laser wavelength),

i.e., $\omega = 1.7 \times 10^{14} \text{ s}^{-1}$, and taking $v_z(0)/c \approx 1.0 \times 10^{-2}$, one finds that $B(0) < 6 \text{ kG}$. Of course, there are other restrictions incorporating the spatial dimensions of the acceleration region, but they are not as stringent as the one just stated.

Suffice it to say that the acceleration process will give the electrons a final energy of ξ_T as they reach the opposite reflector which, in this case,

becomes the cathode in the DC conversion process. Thus, the energy absorbed by the electrons during the acceleration process is $\xi_T - \xi_0$ thus inducing a potential difference V between the two cavity reflectors of

$$V = \frac{\xi_T - \xi_0}{e}$$

Analysis shows that the energy gained by the electrons in this process is proportional to the square of the electric field strength within the cavity.

Problems That Remain to be Solved

Of the several potential problem areas that will most likely become apparent, the most obvious one has to do with heat dissipation due to losses incurred in whatever material is used for the reflectors. Related to this, there is the issue of material erosion on the reflector that is to collect the accelerated electrons. Hopefully these obstacles can be overcome during a prototype development of this electromagnetic wave rectification method.

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